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A Collaborative International Approach to Store Separation

A. Cenko, Ph.D.; J. Lee, Ph.D.; and E. Hallberg, Ph.D.
NAVAIR, Patuxent River, Maryland
N. Matheson, Ph.D.
Defence Science and Technology Organization, Melbourne, Australia
A. Benmeddour, Ph.D.
National Research Council, Ottawa, Canada
B. Jolly
Air Force Seek Eagle Office, Eglin AFB, Florida
J. Bent
Northrop-Grumman, Rolling Meadows, Illinois

In 2005, in support of Northrop Grumman's efforts to market the Litening pod to the Australian and Canadian governments for use on their F/A-18A/B/C/D aircraft, Northrop Grumman contracted Naval Air Systems Command to support flight certification of the Litening pod and the associated pylon mounting system on station 4. The goal was to clear the GBU-12, GBU-38, MK-84, Dual AIM-120s, and FPU-8 fuel tank adjacent to a Litening pod on station 4 to the present TACMAN limits (with an adjacent advanced targeting forward looking infrared). Before the Litening pod effort, the Navy had two choices to clear new aircraft/store configurations: wind tunnel test or the build up approach (also known as hit or miss method). Both of these methods had serious limitations. Wind tunnel testing required at least 6 months of lead-time and a minimum of $500K. The build up approach consisted of increasing the release airspeed until the store came uncomfortably close to hitting the aircraft/ adjacent stores. However, for quick turnaround, it was the only choice. This approach was not only very costly, but in some cases might have required a flight clearance recommendation that was too conservative. During the same time frame, the Department of Defense High Performance Computing Modernization Program office funded a joint U.S. Air Force, Army, and Navy Institute for High Performance Computing Applications to Air Armament. The Institute provided the Navy with the capability of using computational fluid dynamics to provide flight clearance recommendations for the Litening pod in a timely and cost effective fashion.

Key words: Computational fluid dynamics; external store separation; military aircraft; targeting pods; wind tunnel tests.

Store trajectories are defined in the Aircraft Axis System, which has its origin at the store center of gravity at release. The origin is fixed with respect to the aircraft and thus translates along the current flight path at the freestream velocity. The axes rotate to maintain constant angular orientation with respect to the current flight path direction. Due to the F/A-18C/D aircraft symmetry, stations 3 and 4 (left side) are interchangeable with stations 7 and 6 (right side), respectively. All data shown are right wing justified (i.e., station 6).

Previous flight test experience on the F-18C aircraft demonstrated that targeting pods mounted on station 4 could have a significant impact on the trajectories of stores from station 3 (Carron 2003). Recently (Benmeddour et al. 2006), Canada has used computational fluid dynamics (CFD) and wind tunnel testing to show

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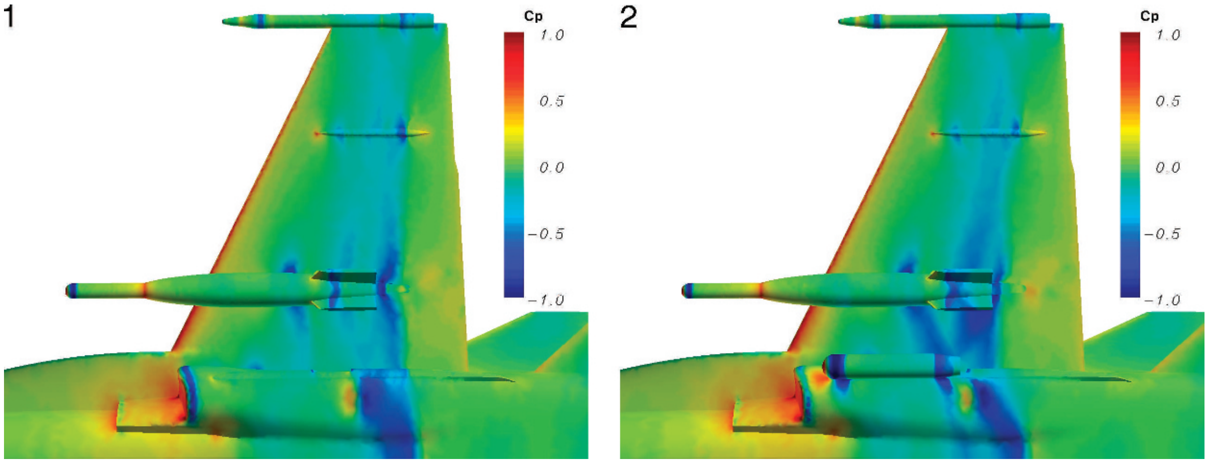


Figure 1. Station 4 clean. Figure 2. Station 4 targeting forward looking infrared.

that this effect was probably due to a transonic shock propagating from the targeting forward looking infrared to the tail of the store at station 3. This effect may be seen in *Figures 1 and 2*, which show the difference in pressure coefficient (*Cp*) distribution for the store at station 3 with and without the targeting forward looking infrared at station 4 at $M = 0.90$.

Because the Litening pod was expected to have a similar effect, Naval Air Systems Command (NAVAIR) established a team consisting of U.S. Navy, U.S. Air Force, Australian Government, and Grumman personnel to determine the separation characteristics of stores adjacent to the Litening pod.

1. Under a separate Institute for High Performance Computing Applications to Air Armament project, the Air Force provided the Navy with the CFD code BEGGAR (Rizk and Ellison 2002) and the associated geometry files for the F/A-18C, GBU-12, GBU-31, GBU-38, MK-82, MK-83, MK-84, and FPU-8 stores. The GBU-12, GBU-31, GBU-38, MK-82, MK-83, MK-84, and FPU-8 were all cleared to their end points using BEGGAR CFD calculations.
2. The GBU-12 was the first case where the Navy used a CFD calculation to flight test a store at its transonic end point without the usual buildup approach. This was also the case for the MK-83 and FPU-8 fuel tank.
3. The MK-82 was the first time that the Navy cleared a store to its end point with no flight testing. This was also done for the AGM-65 and laser guided training rounds stores.
4. A newly developed Matrix Laboratory (MATLAB) tool was used to integrate the flight test telemetry results. This resulted in an excellent match with all the flight test releases, with most stores cleared to the tactical manual (TACMAN) end point in one or two flights.
5. Usually, both photogrammetric and telemetry data are used to determine safe separation. Due to the time constraints of the program, the photogrammetric data were not analyzed. The excellent match with pre-flight predictions achieved by the team convinced NAVAIR to bypass the customary photogrammetrics analyses.

The results described above were based on CFD analyses, and have been described in detail in Cenko (2006, 2006), Cenko et al (2007), and Hallberg and Cenko (2007). This article describes work that has been performed since and concentrates on the stores where wind tunnel testing was deemed necessary.

Discussion

Because of cost and time constraints, the Litening pod effort could not use wind tunnel testing to clear all the desired configurations. Fortunately, the Institute for High Performance Computing Applications to Air Armamen had demonstrated (Cenko 2006) that CFD could be used to replace the wind tunnel for store separation purposes. It was therefore decided that CFD would be used to the maximum extent for this program. To date, eight stores have been cleared to their TACMAN limits using this approach, at an estimated cost savings (Cenko et al. 2007) of more than $1,500,000. An example of the correlation between the CFD predictions and flight test results may be seen for the FPU-8 fuel tank separating from the F-18C station 7 in *Figures 3 and 4*.

The eight stores that were cleared using CFD alone, and which probably represent the applicability limit of

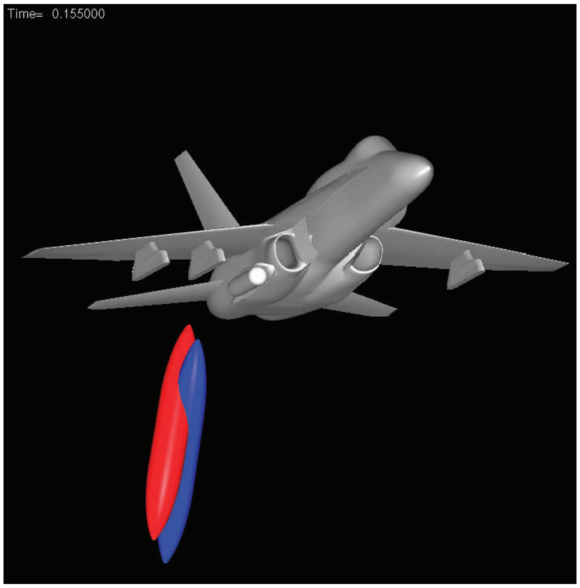


Figure 3. Fuel tank trajectory at M = 0.95.

CFD, had several characteristics that made the approach possible. The hierarchy of store separation difficulty, in decreasing order, can be described as follows:

1. new store on new aircraft,
2. existing store on new aircraft,
3. new store on existing aircraft,
4. existing store on existing aircraft (new configuration),
5. existing store on modified aircraft (previously cleared configuration).

All the examples shown fell in the last category. The reason that CFD was a practical alternative was that there existed substantial wind tunnel and flight test data for both the F/A-18C/D aircraft and the stores that were tested. Because the aircraft modification only affected one station, it was reasonable to calculate the incremental effects using CFD. For cases where large amounts of test data are required, the wind tunnel has no match at the present time.

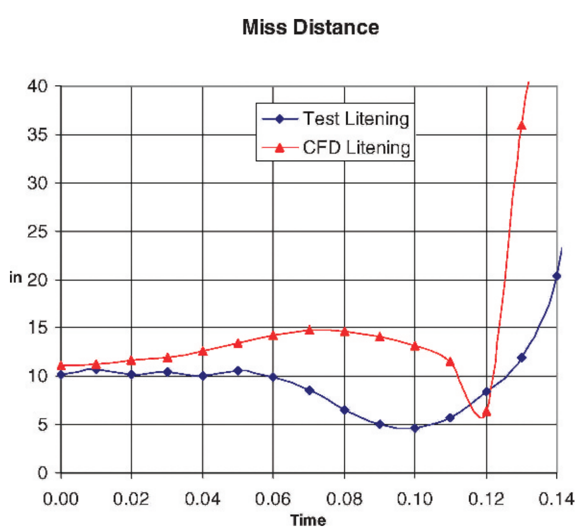


Figure 4. Fuel tank miss distance at M = 0.95.

Figure 5. Dual AIM-120 at carriage.

Even when all these conditions are met, the need for wind tunnel testing has not been eliminated. Because analysis indicated that the Dual AIM-120 configuration might represent a flight safety risk, the Defence Science and Technology Organization (DSTO) in Melbourne, Australia, conducted a wind tunnel test of the configuration. This is the first case where the Navy conducted a store separation wind tunnel test where the aircraft was mounted on its plane of symmetry. Analysis also indicated that the GBU-32, GBU-38, as well as their dumb bomb variants, would have trouble separating from the BRU-55 (CVER, multiple bomb) rack on station 3. Testing in the DSTO tunnel is planned for these configurations.

Dual AIM-120 configuration

As may be seen in *Figure 5*, the Dual AIM-120 assembly has very little clearance between the inboard fin and the Litening pod air intake. For this reason, a store separation wind tunnel test was required before any flight clearance. As Australia was at that time testing their F-18C configuration in the DSTO 0.8-m wind tunnel, it was decided to conduct this test in Australia. This reduced the cost to the program by more than a factor of two.

DSTO 0.8 meter transonic wind tunnel

The DSTO 0.8-m transonic wind tunnel was constructed in the late 1990s, and it became operational in March 2000. It is a closed-circuit continuous flow tunnel with a two-stage axial flow compressor powered by a 5.3 MW variable speed electric motor. The tunnel operates in the transonic speed regime from a Mach number of 0.3 to 1.2 in a continuously

variable mode and Mach 1.4 with a fixed nozzle. It can be pressurized to 200 kPa absolute or depressurized to 30 kPa absolute using a plenum evacuation system, which has a single-stage centrifugal compressor driven by a 2.6 MW induction motor giving evacuation flow rates from the 3.1 m diameter plenum of up to five percent of the circuit air mass flow. Two ULVAC type PKS 060 oil rotary vacuum pumps are used for fine control at pressures below atmospheric. The Reynolds number ranges from 3×10^6 per m at 50 kPa and Mach 0.3, to 28×10^6 per m at 200 kPa and Mach 1.0. The test section is 0.81 m wide, 0.81 m high, and 2.7 m long, with slotted (six slots/wall) and solid interchangeable sidewalls, and a slotted floor and ceiling. The tunnel is equipped with a water cooled heat exchanger, air driers, and screens.

The tunnel has three model support systems: a vertical strut pitch-roll model support used mainly for free-stream tests, a sidewall model support (485-mm-diameter turntable in the solid sidewall) used mainly to mount centerline or half-models for use as the parent aircraft in stores tests, and a six degree-of-freedom store model support to move a store in the vicinity of the centerline model. The store support has a roll drive, a pitch drive, two independent yaw drives ("double yaw" system), and an axial drive. It is mounted on the port side of the vertical strut of the main model support, and it utilizes the vertical motion of this strut to move a store model independently of a model on the sidewall support. The model supports are operated remotely via the control and data acquisition system to provide accurate location and orientation of a model during a test.

A control and data acquisition system controls and monitors all tunnel operations, test parameters, and model support movements. All systems are started, controlled, and stopped from an operator console using touch screens and a keyboard. The tunnel can be operated in an "automatic" mode that steps through a test program automatically, or it can be operated in a single step "manual" mode. Data can be acquired and displayed in near real time.

F-18C and Dual AIM-120 wind tunnel model geometry

The tests were carried out using nine percent scale models of the F-18C aircraft, the AIM-120 missiles and their racks, and the Litening AT pod. All models were built to a tolerance of ± 0.2 mm, and model surfaces were polished. The AIM-120 missiles were mounted on LAU127 racks (Dual AIM 120/LAU127 assembly), which, in turn, were mounted on a LAU115 rack. The F-18C model was made mainly from high strength aluminum with some stainless steel fittings and flow-through inlet ducts. The wing leading and trailing edge flap angles can be changed via servo motors or fixed at preset angles.

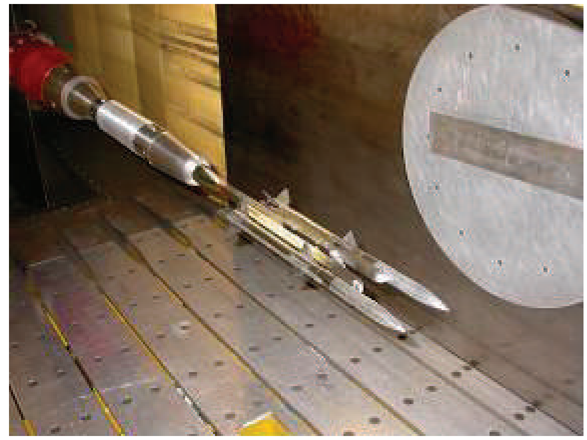


Figure 6. Dual AIM-120 assembly on pitch-roll rig.

Freestream tests were carried out with the Dual AIM 120/LAU127 assembly mounted on a six-component strain gauge balance and sting attached to the main pitch/roll rig as shown in *Figure 6*.

The Dual AIM-120/LAU127 grid tests were carried out with the same assembly mounted on the strain gauge balance and sting attached to the six degree-of-freedom store support system. *Figure 5* shows this assembly close to the LAU115 rack on the F-18C half model fitted with the Litening AT pod attached to the sidewall turntable. The very small clearance between the aft upper port fin and the pod can be seen in this figure. The horizontal tail was not fitted during the grid tests because of the potential for store support sting fouling.

Dual AIM-120 freestream test results

Wind tunnel separation data were obtained using a 0.09 scale, the F-18C/D model, and associated store hardware described above. Freestream and aircraft proximity (grid) data were taken at the DSTO 0.8 m (2.62 feet) transonic wind tunnel in Melbourne, Australia, using the specially designed rig to hold the Dual AIM-120 configuration. Freestream data were obtained for the Dual AIM-120 at constant yaw angles at selected Mach number and angle of attack combinations. Grid data were obtained along vertical rays emanating from the store carriage point.

Because the Dual AIM-120 configuration could not use a conventional aft mounted sting, both store off and on wind tunnel freestream data were taken to determine the effects of the mounting system on the store characteristics. The store off results were

subtracted from the store on data to represent the store alone freestream characteristics.

The freestream values for normal force coefficient (C_N) and pitching moment coefficient (C_m) appeared reasonable and matched previous results. However, there was a large discrepancy in side force coefficient (C_Y), rolling moment coefficient (C_l), and yawing moment coefficient (C_n) at zero sideslip angle (beta). Since the configuration is symmetric about the y axis, there should be no side force, rolling, and yawing moment for betas equal to zero. Apparently, the shroud mounting system used to correct for the sting effects affected these data. For this reason, a store sideslip sweep at zero store angle of attack was also taken.

The rolling moment variation with betas changed sign for yaw angles greater than +4 or less than −4 degrees. The normal force also departed from near zero for betas greater than 4 or less than −10 degrees. The behavior for the pitching and yawing moments is similar for sideslip angles greater than +4 or less than −6 degrees *(Figure 7)*.

Clearly, the store aerodynamic data are suspect for yaw angles exceeding 5 degrees. These can be attributed to the sting assembly that was used. However, since the Dual AIM-120 configuration would hit the Litening pod if the yaw angle exceeds 2 degrees in the first 0.15 seconds, this effect is not considered significant. These effects may better be seen in *Figure 8*, which is a carpet plot of the Dual AIM-120 freestream yawing moment.

Wind tunnel grid data

Since the DSTO F-18 wind tunnel model is mounted at its plane of symmetry on the tunnel wall, only the right side of the aircraft could be tested. Therefore, the Litening pod, which is mounted on station 4 on the aircraft, was mounted on station 6 on the model.

Forty-five Grid runs were taken for the Dual AIM-120 configuration at various Mach numbers, aircraft angles of attack (3, 6, and 9), and store attitudes (store pitch angle = 0, +10, −10; store yaw angle = 0, +6). Twelve runs were repeated for the Litening pod removed to determine the effects of the Litening pod on the store forces and moments.

As may be seen in *Figure 9*, the Litening pod causes a large increase in nose down pitching moment and a small increase in yawing moment close to carriage. The normal force, side force, and rolling moment are not significantly affected *(Figure 10)*. Note that none of the coefficients except for side force approach zero at the furthest point away from carriage (11 feet full scale). Clearly, the last grid point still feels the effects of the aircraft flow field.

Trajectory simulations

The principal reason for acquiring freestream and grid data is to conduct offline trajectory simulations. As a first step in validating the wind tunnel data, flight test trajectories are compared with the trajectory simulations for the same conditions. Flight test data existed for $M = 0.82$ at 5,000 feet for the F-18C aircraft with AIM-7 instead of Litening pod on station 6. Wind tunnel and CFD predictions have demonstrated (Benmeddour et al. 2006) that the effects of the AIM-7 on station 6 are similar to the station being empty. The Navy generalized separation package, NAVSEP (Ray in press), was used to predict the trajectories released from station 7 using the grid data without the Litening pod. As may be seen in *Figure 11*, the predicted trajectory displacements are in excellent agreement with the flight test data for this case. The predicted pitch attitudes are also in excellent agreement *(Figure 12)*, whereas the yaw attitude is slightly underpredicted and the roll overpredicted.

Because the grid and freestream predictions give a good match to the clean F-18 flight test data, we can use the NAVSEP code to determine what the effects of the Litening pod would be on the Dual AIM-120 trajectory. As may be seen in *Figure 14*, there is a considerable difference between the predicted pitch, yaw, and roll attitudes for adjacent Litening pod and the flight test data for the aircraft with the AIM-7 on station 6.

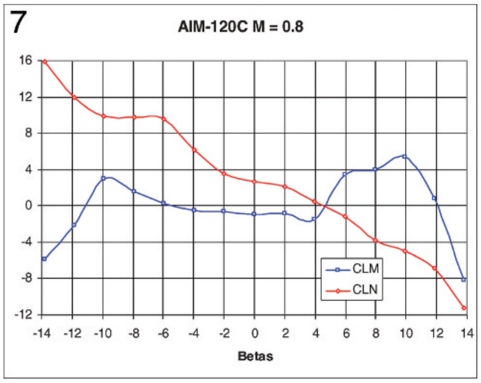
Miss distances

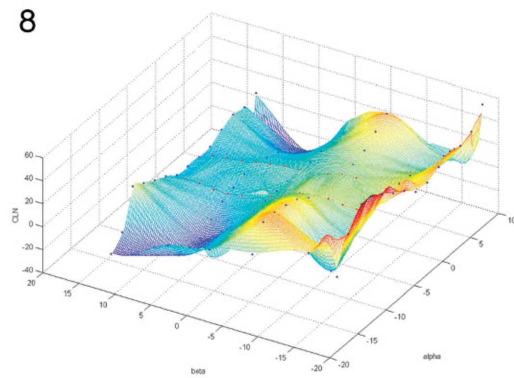
The miss distances for the Dual AIM-120 next to the AIM-7 flight test at $M = 0.82$ is shown in *Figure 15*. This distance is calculated using the clean station 6 grid data *(Figures 11 and 12)*. The other miss distance is that for the predicted Litening pod configuration *(Figures 13 and 14)*.

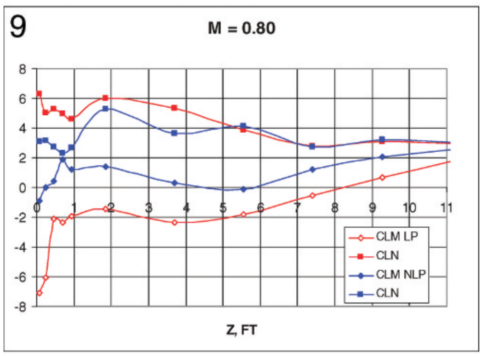
It appears that the presence of the Litening pod on station 6 makes little difference in the miss distance, even though it had a large influence on the pitch, yaw, and roll attitudes. The reason for this is that the increased roll is favorable, as it tends to move the tail surface away from the Litening pod. The miss distance decreases only when the Dual AIM-120 configuration is well below the Litening pod.

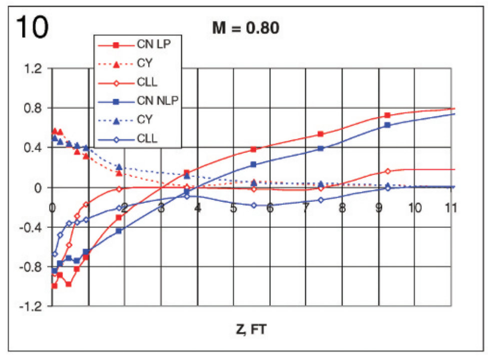
Flight test considerations

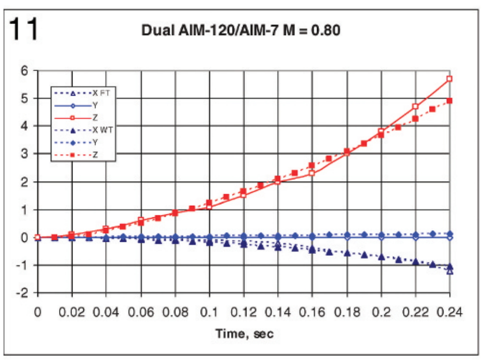
All of the trajectory simulations conducted offline after the test indicate that the Dual AIM-120 configuration should be able to separate safely from the F-18C aircraft with adjacent Litening pod.

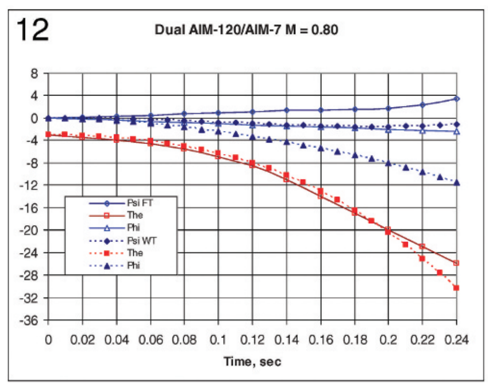


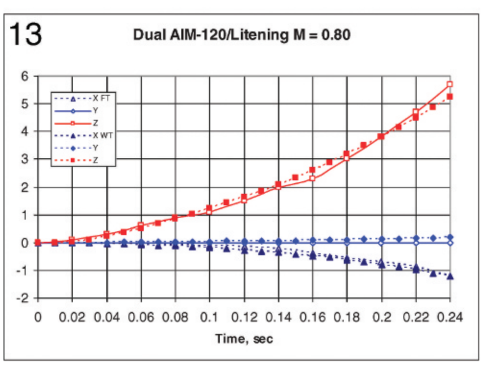












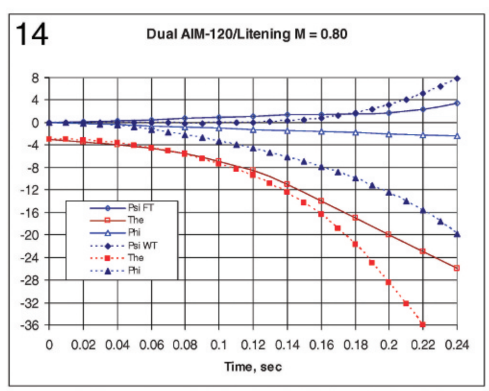


Figure 7. Dual AIM-120 freestream data. Figure 8. Dual AIM-120 freestream carpet plot. Figure 9. Dual AIM-120 CLM and CLN grid data. Figure 10. Dual AIM-120 CN, CY, and CLL grid data. Figure 11. Dual AIM-120 Displacement Station 3 clean. Figure 12. Dual AIM-120 Attitude Station 3 clean. Figure 13. Dual AIM-120 Displacement Station 3. Figure 14. Dual AIM-120 Attitude Station 3.

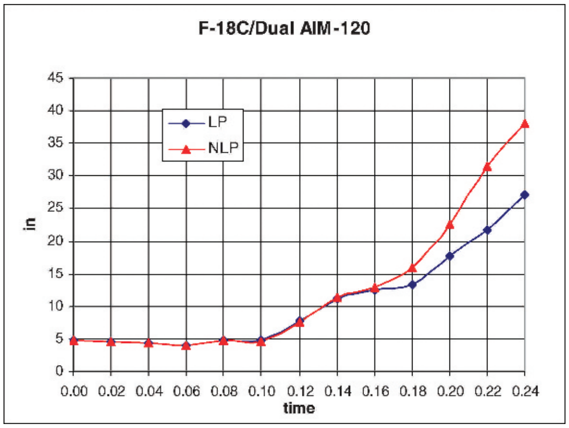


Figure 15. Litening pod effect on miss distance.

However, wind tunnel test predictions have been known to imperfectly (Cenko 2006) match flight test results. In particular, the test data are suspect for yaw angles in excess of 5 degrees, since the freestream data were inconsistent there. Because the grid data agreed with pretest CFD predictions *(Figure 16)* and parametric variation of the aerodynamic loads did not indicate any causes of concern, a flight test for this configuration is planned.

Conclusions

There are several organizations that promote national and international collaboration. The Institute for High Performance Computing Applications to Air Armament project provides an institute for the Air Force, Army, and Navy to share CFD tools and expertise between the U.S. Department of Defense and U.S. contractors. The Research and Technology Organization provides a similar mechanism for NATO participants, and The Technical Cooperative Program serves a similar role for English speaking countries. The American Institute of Aeronautics and Astronautics and International Test and Evaluation Association provide forums where this work can be presented.

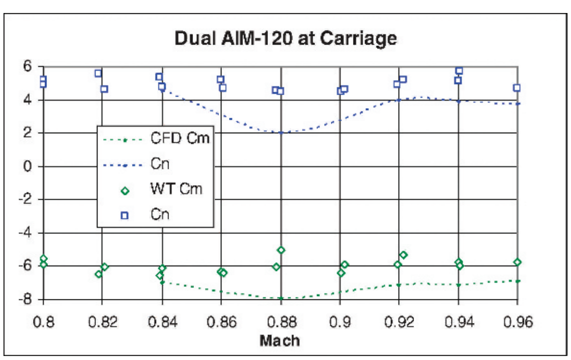


Figure 16. Wind tunnel and computational fluid dynamics moment comparison.

Collaboration, when properly structured, can have a synergistic effect on the process.

The F-18C/Litening pod integration benefited considerably from both the national and international collaboration involved. Because of the Institute for High Performance Computing Applications to Air Armament project, the Air Force provided the Navy with the CFD tools that enabled a cost effective and timesaving approach to the problem. Canadian wind tunnel test data enabled CFD tool validation, and testing in the Australian 0.8 m tunnel saved the program considerable time and money.

Clearly, collaboration is a win-win proposition for all the parties involved in store separation flight clearances. The laws of aerodynamics are the same for the Air Force and Navy, as well as overseas. Collaboration can avoid unnecessary duplication of effort, particularly for a common aircraft that has extensive use among U.S. allies (F-18 for the Navy and the F-15/16 for the Air Force). However, because of International Trafficking in Arms restrictions, international collaboration is becoming increasingly more challenging. ❑

A. Cenko, Ph.D. is a member of the Applied Aerodynamics and Store Separation Branch at the Naval Air Systems Command. He has almost thirty years of experience in the application of CFD, wind tunnel and flight testing techniques in the area of aircraft/store integration, and has published over fifty papers in the field. For the past five years, he has served as manager of the store separation technical area for the Institute for HPC Applications to Air Armament (IHAAA). Dr. Cenko was also the NAVAIR chair and visiting professor at the U.S. Naval Academy and associate professor of engineering at Hofstra University.

Jae Lee, Ph.D. is a member of the Applied Aerodynamics and Store Separation Branch at the Naval Air Systems Command. He primarily works for the JSF Program Office in the area of Weapon Integration. Before he joined the Navy, he worked for Air Force SEEK EAGLE Office for four years. Dr. Jae Lee obtained a bachelor degree in aerospace engineering from Illinois Institute of Technology, and master's and Ph. D. degrees in aerospace engineering from the Georgia Institute of Technology.

Eric Hallberg, Ph.D. is an assistant professor in the Aerospace Engineering Department at the United States Naval Academy in Annapolis, MD. In addition to store separation applications, his research interests include guidance and control of unmanned air vehicles. Prior to joining the faculty at the Naval Academy, Dr. Hallberg

worked in industry for General Dynamics and was a naval flight officer in the U.S. Navy.

DR. MATHESON, Ph.D. was awarded a doctorate in philosophy in fluid dynamics from the University of Melbourne, Australia, in 1972. He then commenced work as a research scientist with the Aeronautical Research Laboratory, which is now part of the Defence Science and Technology Organization (DSTO), Department of Defence, Australia. In 1981 he was promoted to a senior research scientist position where he carried out extensive research a wide range of subjects including the hydrodynamics of surface and subsurface ships, and the aerodynamics of specialized flight vehicles, missiles, towed targets, and decoys, as well as helicopter aerodynamics and stability. In 1992 he was promoted to the position of head of Flight Mechanics Technology and Wind Tunnels, as a principal research scientist, where he was responsible for a wide range of research and activities, including the design and construction of a new transonic wind tunnel, which was completed in 2000, and for the testing in that tunnel. In 2002 he became the head of Experimental Aerodynamics where he was responsible for the tests and research activities in the DSTO transonic wind tunnel, the low speed wind tunnel and the water tunnel. His work included missile testing, primarily for predicting stores trajectories, testing of new fighter aircraft, and the development of advanced instrumentation for the facilities. In 2004 his responsibilities were widened to include vibration and aeroelasticity applicable to both fixed and rotary wing aircraft, mainly in relation to safe stores carriage and release. Dr Matheson was also the DSTO representative for the Supersonic Tunnel Association—International from 1990 until 2004.

A. BENMEDDOUR, Ph.D. obtained a bachelor degree in mechanical engineering from ècole Polytechnique of Algiers, Algeria, a master's degree in mechanical engineering from Sherbrooke University, Canada, and a Ph. D. in mechanical engineering from ècole Polytechnique of Montreal, Canada. Dr Benmeddour joined the Institute for Aerospace Research of the National Research Council of Canada in 1996. He is a senior research officer, and his main area of research is the application of computational fluid dynamics to solve various challenging applied aerodynamics problems, including store separation.

BRUCE JOLLY is the deputy director for TEAS support to the 46 TW at Eglin AFB where he works in the field of store compatibility and is the technical lead for the Air Force SEEK EAGLE Office Computational Aeromechanics Team. He has degrees from Auburn University, University of Dayton, and Liberty Theological Seminary. He is an American Institute of Aeronautic and Astronautics associate fellow and licensed professional engineer.

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